Chapter 4

Layered Substrates

4.1 Introduction

The significant result of the previous chapter is that guided mode (surface wave) losses can be avoided on substrates with thicknesses of an odd integral multiple of a quarter wavelength through the use of broadside twin elements. Although significant improvements in integrated efficiencies over the single element cases were shown in Chapter 3, there are several difficulties for uniform thick substrates. In particular, for a single quarter wavelength thick substrate the E- and H-plane beam patterns are broad and asymmetric. It was also found, however, that the patterns improved when somewhat thicker substrates were considered (such as a three quarter wavelength thick substrate). Unfortunately, although the thicker substrates had better beam patterns, the integrated efficiencies were significantly reduced compared to the quarter wavelength thick substrate; this effect is very severe if high dielectric constant materials such as Si or GaAs are used as the supporting substrate. For the thicker substrates, the power lost to various guided waves clearly showed that the limitations are due to the large number of modes excited. In this chapter we consider the use of layered substrates backed by a ground plane (Figure 2.1) to remedy some, if not all, of these shortfalls. The problem is to determine if the dielectrics can be layered in such a way that the structure suppresses guided modes, or at least all but one mode, while still providing a useful beam pattern.

Here, we present calculations of the radiation characteristics for three and five layer dielectric stacks with beam patterns appropriate for a feed antenna in an imaging system. We also show results for both dipoles and slots to illustrate the similarities and differences betwen these two sources. Our discussion is limited to a few specific cases which should be useful for millimeter wave applications. The first limitation is in the choice of dielectrics: only common, low loss materials will be considered. These include GaAs ($\varepsilon_r = 13$), quartz ($\varepsilon_r = 4$), and polyethylene ($\varepsilon_r = 2.4$). The second limitation is to consider only layers that are a quarter of a dielectric wavelength thick. We will show that stacks of odd numbers of these layers with properly chosen dielectric constants can improve the efficiency of both slot and dipole antennas. In the final section we present measurements of beam patterns of several structures. Measurements were made on 10GHz models. We have found reasonable agreement between measurements and caclulations. Again, infinitesimal sources were used to calculate all of the efficiencies and most of beam patterns of the dielectric structures considered. The only place element length was considered is in section 4.4 where experimental and calculated results were compared, and, as stated before, the finite length element gave results nearly identical to the elemental source.

4.2 Three Layer Case

There are obviously many choices of dielectric constants and thicknesses that one could choose for a layered structure. In this section we will illustrate the main considerations used in determining the dielectric constants and layer thicknesses necessary to increase the radiation-to-air efficiency of slots and dipoles, as well as what is required to produce a desired beam pattern. The discussion will focus mainly on a three layer structure, which will serve as a prototype exhibiting most of the features of structures with more layers.

One choice of layer thicknesses which can increase the power radiated to air is to make all the layers an odd integral multiple of a quarter of a wavelength thick. To see this it is simplest to consider a simple transmission line model representing the boresight behavior of the dielectric stack. When the thicknesses are odd integral multiples of quarter wavelengths the surface impedance looking into a stack of three layers from the ground plane is:

$$Z_{in} = \frac{Z_1^2 \, Z_3^2}{Z_2^2 \, Z_o} = \frac{\varepsilon_2}{\varepsilon_1 \, \varepsilon_3} Z_o \tag{4.1}$$

where ε_1, ε_2, and ε_3 are relative dielectric constants of the three layers, numbered sequentially starting with the layer closest to the ground plane (see Figure 2.1), and Z_o is the impedance of free space. This structure can, of course, be extended to an arbitrary number of layers. In that case, the dielectric constants of the odd-numbered layers will appear in the denominator, while the dielectric constants of the even numbered layers will appear in the numerator. From Eq. (4.1) we see that the impedance looking into the stack from the ground plane can be reduced by choosing ε_1 and ε_3 to be larger than ε_2. A slot antenna in the ground plane, which behaves like a voltage source, would then deliver more power into the dielectric stack than directly into air. This results in a boresight front-to-back power division of $(\varepsilon_1 \, \varepsilon_3)/\varepsilon_2$, where radiation into the dielectric is "front" radiation, and that radiated directly to air is "back" radiation.

In contrast to the slot, a dipole antenna element is displaced one quarter wavelength from the ground-plane, at the interface between layers 1 and 2. This quarter-wave displacement transforms the "short" circuit of the ground plane into an open circuit in the plane of the dipole. Our boresight transmission line model now consists only of layers 2 and 3, followed by air. The impedance looking through this stack is given by :

$$Z_{in} = \frac{\varepsilon_3}{\varepsilon_2} Z_o \qquad (4.2)$$

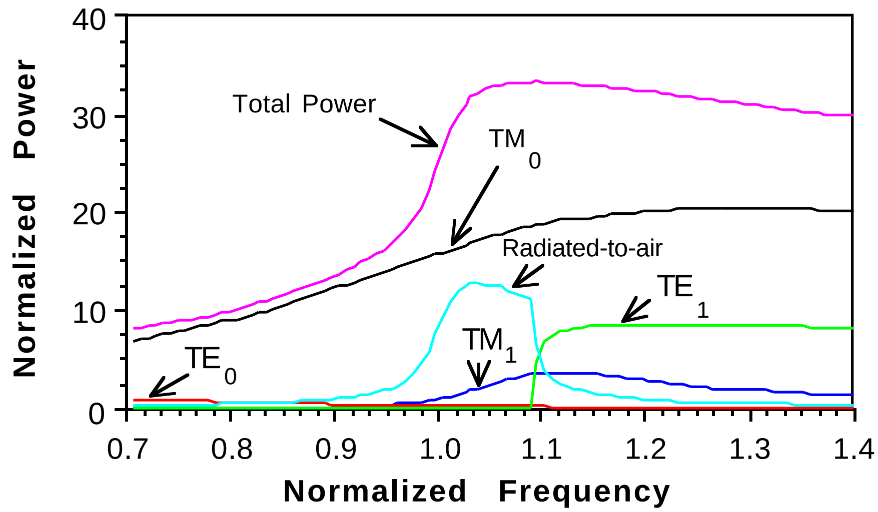
Since a dipole is modeled as an electric current source, it will deliver maximum power towards the air (the load) when the impedance of the stacks is maximized, i.e. when $\varepsilon_3 > \varepsilon_2$. Thus, the conditions for maximizing the radiation-to-air impedance in the plane of the dipole, and minimizing the radiation-to-air impedance in the plane of the slot antenna, correspond to the same structures. Because of this, we will be able to directly compare the behavior of both dipoles and slots for each specific dielectric stack, understanding that the dipole will always be at the interface between the ε_1 and ε_2 layers.

We will refer to the use of an odd number of quarter wavelength thick layers as "resonant," in keeping with the terminology used by Jackson and Alexopoulos [15,16] For this reason, we also normalize all frequencies to the frequency at which the layers are a quarter of a wavelength thick. The beam patterns shown in this section are for a normalized frequency of one unless otherwise specified. The boresight gain, G, of the antenna and substrate configuration is defined as:

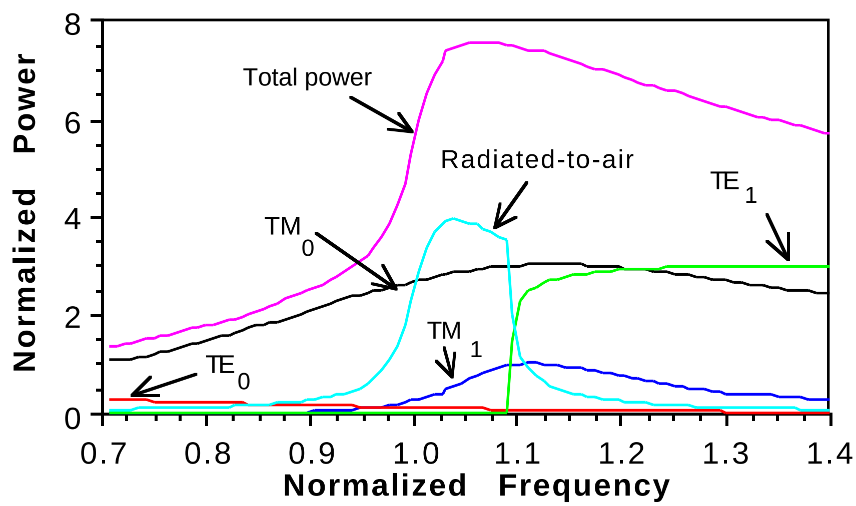
$$G = \frac{P(\theta, \phi, r)\ 4\pi r^2}{P_{total}}\Big|_{\theta=0,\ \phi=0} \tag{4.3}$$

where P is the power density radiated to air by the source, θ and ϕ are the same angles as before, r is the distance from the source, and P_{total} is the total integrated power radiated by the element including the surface wave power and, in the case of the slot, the power radiated directly to air (i.e. the denominators of equations (2.9) and (2.10)). The gain will increase as the power delivered to the surface waves is decreased, thus an increase in efficiency will also yield an increase in gain.

The first structure we consider is one with $\varepsilon_1 = 13$ (GaAs), $\varepsilon_2 = 2.4$ (polyethylene), and $\varepsilon_3 = 13$ (GaAs), which should be practical at millimeter wave frequencies. We will refer to this type of structure as symmetric, since the substrate (layer 1) is the same as the last layer (layer 3). The distributions of power between guided modes and radiation-to-air for a single slot or a single dipole on this stack are shown in Figure 4.1. The powers in Figure 4.1 are normalized to the power the element would radiate in free space as was done in [1,2]. It can be seen that the dipole has more power radiated to air than coupled to the dominant guided mode (the TM_o mode), while the slot delivers most of its power to the TM_o mode. As discussed in Chapter 3, since there is significant power coupled to only one guided mode here, it should be possible to use in-phase twin elements to cancel this coupling, thus improving efficiency. Here it is the TM_o mode which must be cancelled for both the slot and dipole. This mode is launched primarily broadside to a slot, and primarily off the ends of a dipole. To achieve efficient cancellation, then, broadside twin slots should be used,



a) Slot



b) Dipole

Figure 4.1 Normalized power vs normalized frequency for (a) a single slot, and (b) a single dipole on a $\varepsilon_1 = 13$, $\varepsilon_2 = 2.4$, $\varepsilon_3 = 13$ layered dielectric structure.

while twin dipoles would require end-to-end placement [41]. Unfortunately, the design of a simple feed network for end-to-end dipoles is quite difficult; thus, we consider only broadside twin elements in this discussion. Figure 4.2 shows the efficiencies for both single and twin elements, using the method described in Chapter 3 for choosing the spacing of twin broadside slots and dipoles. Due to the cancellation of coupling to the dominant TM_o mode, broadside-spaced twin slot antennas reach a peak efficiency of approximately 80% at the design frequency (i.e. $f_N = 1$), compared to only 30% for a single slot. Note that even though a broadside twin dipole configuration was used, there is still some cancellation of guided mode coupling, resulting in an improvement in efficiency over a single dipole. Twin dipoles, however, are less efficient than twin slots.

It is instructive to compare this case with that of a uniform $\varepsilon_r = 13$ substrate that is $0.75\lambda_d$ thick. For such a substrate the slot antenna is very inefficient (17.7 %), with twin slots providing only a modest increase in efficiency (34%). This is due to the fact that there are several TM modes which are strongly excited for a uniform $0.75\lambda_d$ thick substrate. By making use of the 13-2.4-13 three layer stack it is possible to suppress strong coupling to all but the TM_o mode. Thus the use of twin slots and a three layer stack can improve the efficiency from only 34% to about 80%. The higher order guided modes in this structure carry less power than would a uniform substrate with $\varepsilon_r = 13$, which suggests that introducing "contrast" in the dielectric substrate suppresses the higher order modes.

The beam patterns for single elements on this three layer symmetric stack are shown in Figure 4.3. Note that the patterns for the slot and the dipole are

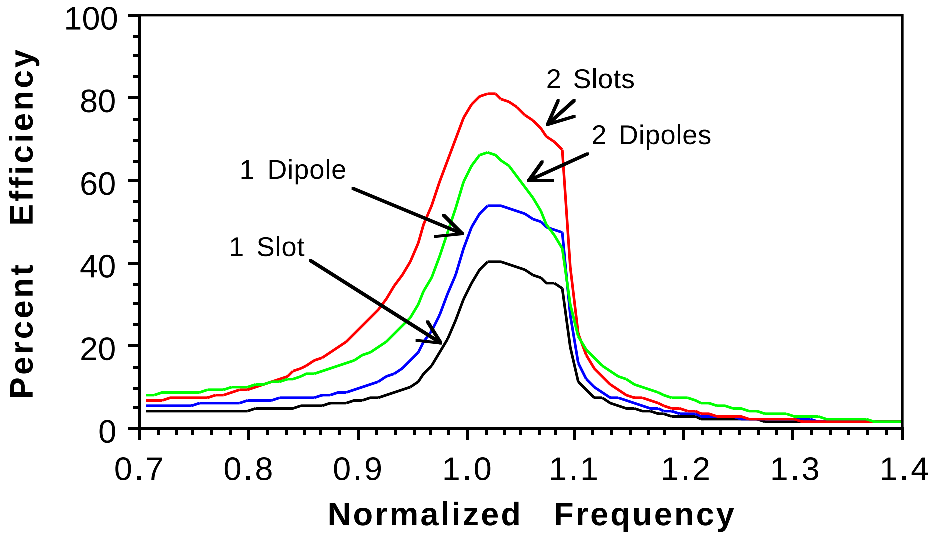


Figure 4.2 Efficiency vs normalized frequency for single and broadside spaced twin elements on a $\varepsilon_1 = 13$, $\varepsilon_2 = 2.4$, $\varepsilon_3 = 13$ layered dielectric structure. The separation for the twin slots is $0.244\lambda_o$ and the separation for twin dipoles is $0.366\lambda_o$ where λ_o is the free space wavelength at $f_N = 1$.

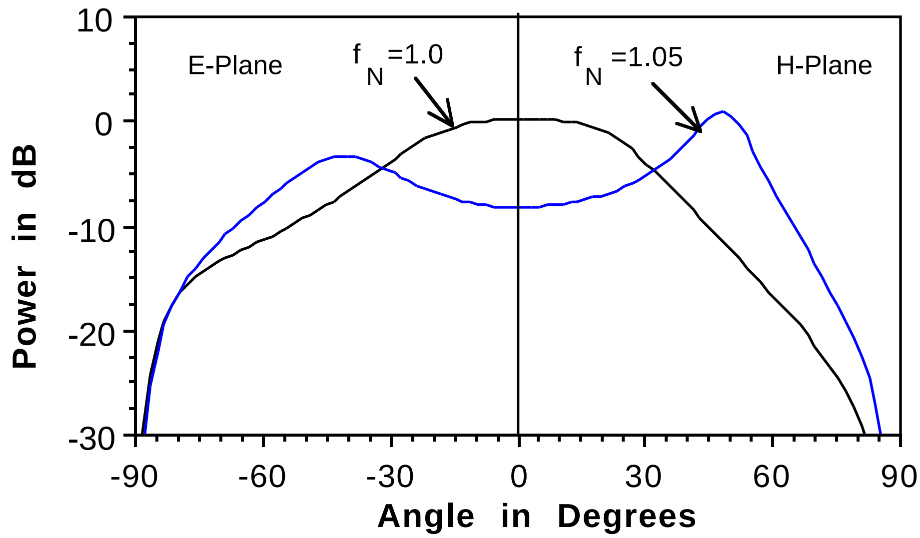


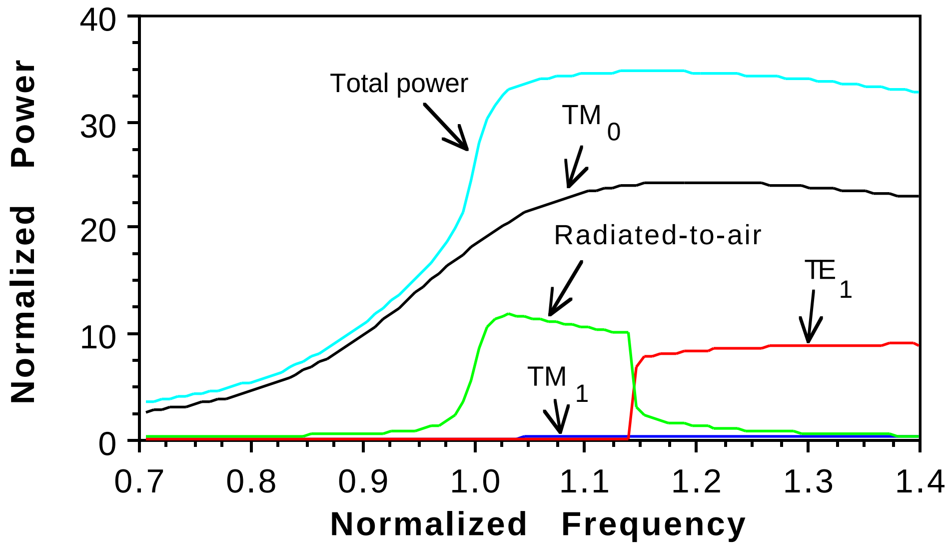
Figure 4.3 Beam patterns for either a single slot or a single dipole on a $\varepsilon_1 = 13$, $\varepsilon_2 = 2.4$, $\varepsilon_3 = 13$ layered dielectric structure. The patterns for the slot and the dipole are indistinguishable. The gain for a single slot is 6.1dB ($10 \log_{10}(G)$), and for twin slots is 10.2dB. The gain for a single dipole is 7.6dB and for twin dipoles is 9.5dB.

indistinguishable, and that the E- and H-plane patterns are nearly symmetric, with a 3 dB beamwidth (half-width, half maximum) of about 25^o. In addition, the beam patterns of twin elements are virtually identical to the single elements. This suggests that the patterns are dominated by the dielectric, not the type of antenna. This is consistent with the view discussed earlier, which showed that the resonant dielectric structures for the dipole and the slot are the same. This feature makes the design of a desirable beam pattern center primarily on the choice of dielectrics, rather than the radiating element.

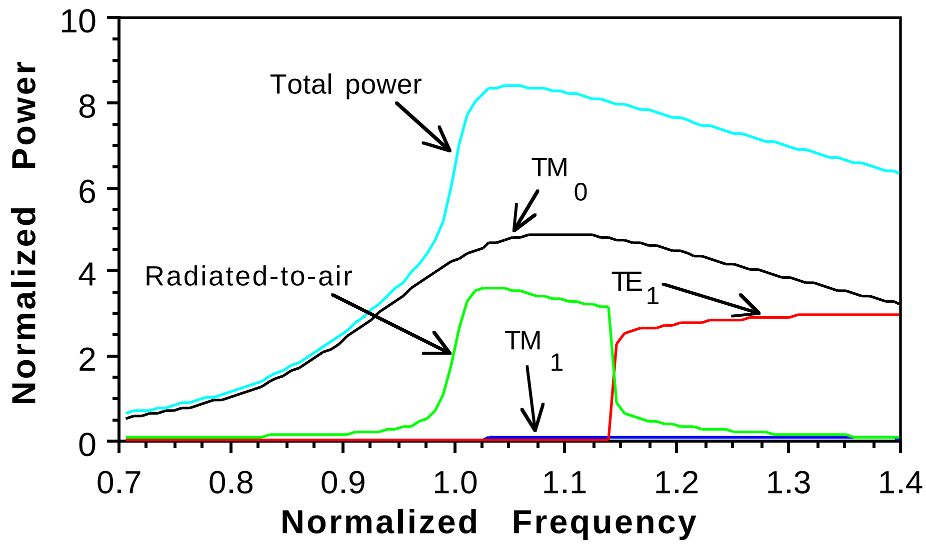
Another important feature of these stacks is illustrated by Figs. 4.2 and 4.3: the peak efficiency for both slots and dipoles is not at the design frequency, but slightly above it. The cause of this effect can be clearly understood when the beam patterns (Figure 4.3) are examined. As the frequency increases beyond that at which the layers are $0.75\lambda_d$ thick (i.e. $f_N > 1$) the beam splits into a "cone" with maxima of about the same amplitude as at boresight for $f_N = 1$, which then move away from boresight towards the horizon as the frequency is increased. Using a transmission line analogy, this is not surprising, since the layers will still be approximately $\lambda/4$ in electrical thickness for $f_N > 1$, at the appropriate non-normal angle of incidence. Since such a lobed-pattern would generally be a very poor feed pattern for a lens, the increase in integrated efficiency at $f_N > 1$ may not translate into an increase in overall system efficiency. In fact, if the frequency is increased enough, the lobes in the H-plane will shift all the way down to the horizon, finally becoming a propagating TE-mode in the substrate. This is why, in Figure 4.1, for both the slot and the dipole, an abrupt decrease in the radiation-to-air power results at the same time the TE_1 mode turns on, while the total power from the element changes only smoothly.

Another interesting three layer stack results if we change the dielectric constant of the middle layer to $\varepsilon_r = 1$ (i.e. an air gap of one quarter wavelength). Figure 4.4 shows the power distribution for a single slot and a single dipole for the 13-1-13 stack. Compared to the 13-2.4-13 stack (Figure 4.1) the main difference at the design frequency is that the power delivered to guided modes other than the TM_o mode has been reduced even further. For instance, the amount of power delivered to the TM_1 mode is reduced by about a factor of six for both the slot and the dipole. Figure 4.5 shows the efficiencies for this stack, which are quite similar to those achieved in the 13-2.4-13 case (Figure 4.2). This is due to the fact that the dominant loss in both cases is to the TM_o mode, which has not been strongly affected by the change in the dielectric constant of layer 2. The beam pattern for the 13-1-13 stack is shown in Figure 4.6. Again the slot and dipole patterns are indistinguishable, and the general characteristics of this stack are quite similar to those of the 13-2.4-13 structure, although the main beam is narrower (3 dB beamwidth of about 15^o, compared to 25^o before).

In both the previous cases the antenna element has been placed on a substrate with $\varepsilon_r = 13$, which is a fairly high dielectric constant. We should also determine the effect of changing the dielectric constant of the substrate (i.e. the layer closest to the ground-plane) to a lower value, for instance $\varepsilon_r = 4$. Figure 4.7 shows the distribution of power between radiation and guided modes for a 4-2.4-13 dielectric stack. We call this an "inverted" structure because the highest dielectric constant layer is the layer farthest from the antenna element. For this



a) Slot



b) Dipole

Figure 4.4 Normalized power vs normalized frequency for a) a single slot, and b) a single dipole on a $\varepsilon_1 = 13$, $\varepsilon_2 = 1$, $\varepsilon_3 = 13$ layered dielectric structure.

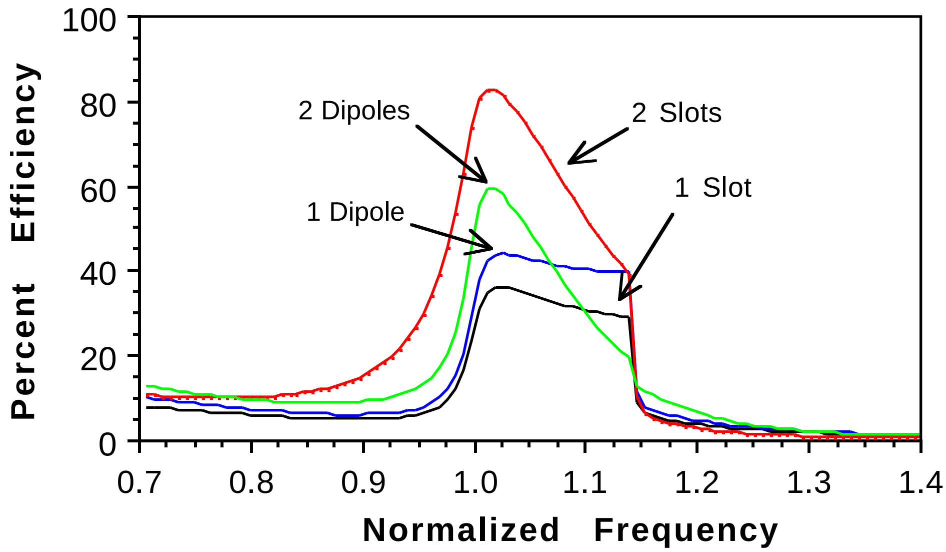


Figure 4.5 Efficiency vs normalized frequency for single and broadside spaced twin elements on a $\varepsilon_1 = 13$, $\varepsilon_2 = 1$, $\varepsilon_3 = 13$ layered dielectric structure. The separation for the twin slots is $0.341\lambda_o$ and the separation for twin dipoles is $0.488\lambda_o$ where λ_o is the the free space wavelength at $f_N = 1$.

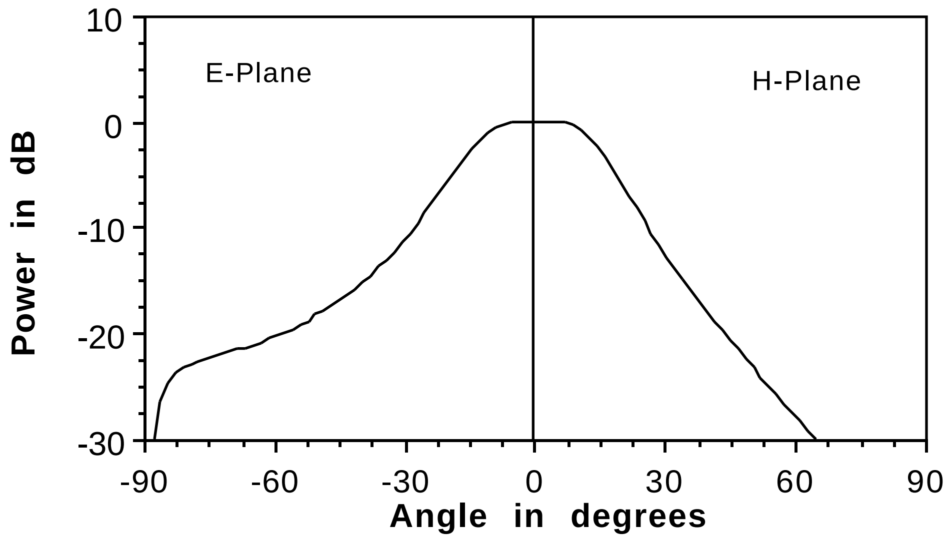
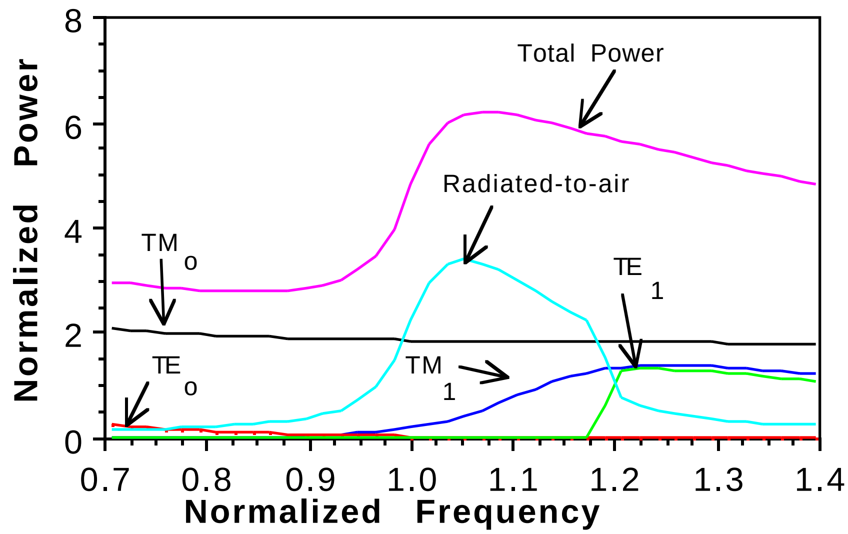
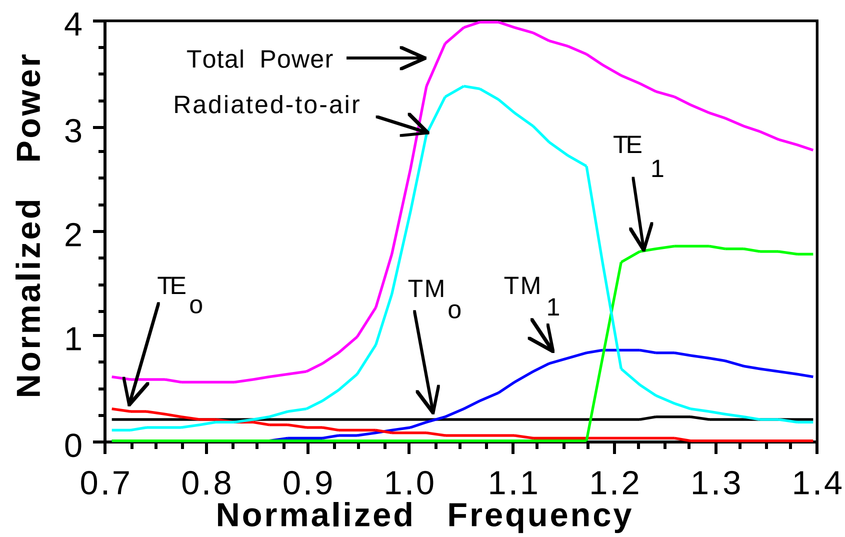


Figure 4.6 Beam patterns for either a single slot or a single dipole on a $\varepsilon_1 = 13$, $\varepsilon_2 = 1$, $\varepsilon_3 = 13$ layered dielectric structure. The gain for a single slot is 9.9dB , and for twin slots is 14.9dB. The gain for a single dipole is 10.8dB and for twin dipoles is 13.1dB.



a) Slot



b) Dipole

Figure 4.7 Normalized power vs normalized frequency for a) a single slot, and b) a single dipole on a $\varepsilon_1 = 4$, $\varepsilon_2 = 2.4$, $\varepsilon_3 = 13$ layered dielectric structure.

stack there is a considerable reduction in power coupled to the TM_o mode compared to the symmetric 13-2.4-13 case (Figure 4.2); comparing the powers delivered to the TM_o mode this reduction is by more than a factor of 10. Note, however, that for a slot there is also a drop in radiation-to-air power by about a factor of four, while the dipole radiation-to-air power remains nearly constant. This is because, as we see from equations 4.1 and 4.2, the boresight power radiated to air for the slot depends on the dielectric constant of the first layer, while the boresight power radiated to air from the dipole only depends on layers 2 and 3. Also note that the power delivered to the other higher-order modes (particularly the TM_1 and the TE_1 modes) relative to the radiation-to-air power is about the same as in the 13-2.4-13 case. The corresponding efficiencies for this structure are shown in Figure 4.8. We see that the efficiencies for the dipoles at the design frequency are significantly improved compared to the 13-2.4-13 structure (due to the dramatic drop in guided mode power relative to radiation-to-air power), while the improvement in efficiency for a single slot is only slightly improved, and for twin slots is almost unchanged.

The 4-2.4-13 structure has similar features to the structure considered in [15] and [16] where a high dielectric constant cover layer was used to improve the efficiency of a "buried" dipole. The argument given in [15] concerning the effect of the high dielectric constant cover layer is that propagating guided modes will have transverse wave numbers such that the transverse dependence of the field will eventually become evanescent in the lower dielectric constant layers. Thus there will be very little field for the slot or dipole to couple to, and, by reciprocity, the guided mode will not be strongly excited. This is certainly true,

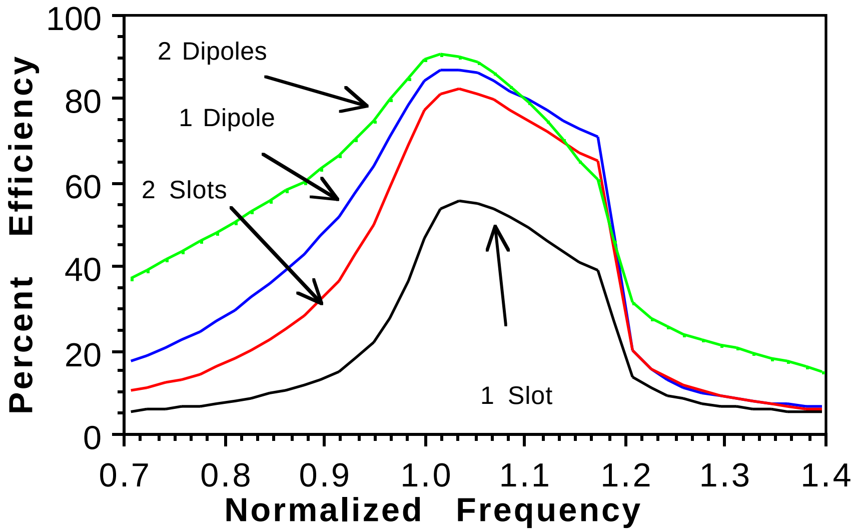


Figure 4.8 Efficiency vs normalized frequency for single and broadside spaced twin elements on a $\varepsilon_1 = 4$, $\varepsilon_2 = 2.4$, $\varepsilon_3 = 13$ layered dielectric structure. The separation for the twin slots is $0.317\lambda_o$ and the separation for twin dipoles is $0.366\lambda_o$.at $f_N = 1$.

but as Figure 4.8 indicates, there is a much greater reduction of power delivered to the TM_o mode in the case of the dipole than in the case of the slot, where the slot is actually placed farther from the high dielectric constant cover layer than the dipole. This suggests that there may be additional factors involved here. The increase in efficiency may also be due to the fact that a dipole over a ground plane has nulls in its radiated fields in the plane parallel to the ground plane. When the dipole is imbedded in a lower dielectric constant medium, the portion of the TM wave fields in the lower dielectric constant layer are refracted more parallel to the ground plane, and are therefore steered more into the direction of the nulls of the dipole. Thus, even though TM waves can propagate exactly parallel to the ground plane, the total power coupled to the wave by the dipole will be significantly reduced, even before the "tail" of the mode becomes evanescent in the low dielectric constant layer. The slot antenna, in contrast, only has nulls in the endfire direction; hence it will always couple fairly well to the TM modes. In this case the only significant advantage of using a lower dielectric constant substrate is to suppress the lowest order TM and TE modes. Note that the use of broadside twin slots introduces a null in the direction broadside to the slots (the direction of the maximum of the TM mode for a single slot) which the single element did not have, thus increasing the efficiency. Since TE modes cannot propagate exactly parallel to a perfectly conducting plane, very little power is delivered to the lower order TE modes for either the slot or the dipole source.

The beam patterns for the 4-2.4-13 structure are shown in Figure 4.9. As in the 13-2.4-13 stack, the dipole and slot patterns, while distinquishable, are virtually identical, and the E- and H-plane patterns are quite symmetric. The use

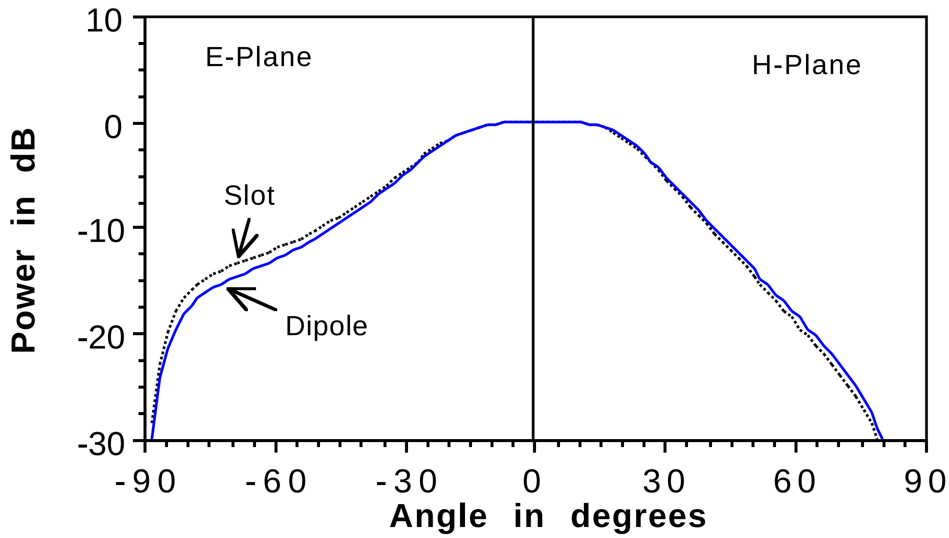


Figure 4.9 Beam patterns for a single slot and a single dipole on a $\varepsilon_1 = 4$, $\varepsilon_2 = 2.4$, $\varepsilon_3 = 13$ layered dielectric structure. The gain for a single slot is 8.4dB, and for twin slots is 11.2dB. The gain for a single dipole is 11.0dB and for twin dipoles is 11.8dB.

of twin elements produces patterns very similar to the single element patterns shown in Figure 4.9. Note that the beam width for this asymmetric stack is very close to that of the 13-2.4-13 stack. The only difference in structure for these two stacks is in ε_1; if we continue to decrease the dielectric constant of the substrate (i.e. layer 1) the beam patterns to will narrow, although this effect is small. Thus, the beam width is determined primarily by layers 2 and 3, which for both of these cases is the same ($\varepsilon_2 = 2.4$ and $\varepsilon_3 = 13$).

Another interesting three layer stack results if we set $\varepsilon_1 = \varepsilon_2 = 4$, with $\varepsilon_3 = 13$. For a slot antenna, the substrate (i.e. the layer directly supporting the antenna) is now effectively one-half of a wavelength thick. The dipole, however, is sandwiched between two quarter-wavelength thick layers. This 4-4-13 stack corresponds to the "type 1" resonance condition discussed in [15] and [16]. The efficiency for this structure is shown in Figure 4.10. Compared to the 4-2.4-13 three layer structure (Figure 4.8), we see that this structure produces slightly lower efficiencies. This is due to the lower contrast between the middle layer ($\varepsilon_2 = 4$ now, compared to 2.4 in two of the previous cases) and the third layer ($\varepsilon_3 = 13$), which causes the slot and dipole to deliver slightly less power to air. There is also slightly more power delivered to lower order guided modes in this case than in the other three layer cases. The higher dielectric constant top layer still provides enough of a contrast to make the structure fairly efficient compared to a uniform $3/4\lambda_d$ thick substrate: 70% for twin slots here, compared to 50% for the $3/4\lambda_d$ thick, $\varepsilon_r = 4$ substrate. Figure 4.11 shows the beam patterns of a single element for the 4-4-13 structure. As before, the patterns of slots and dipoles are nearly the same. Note that this pattern is slightly broader than the

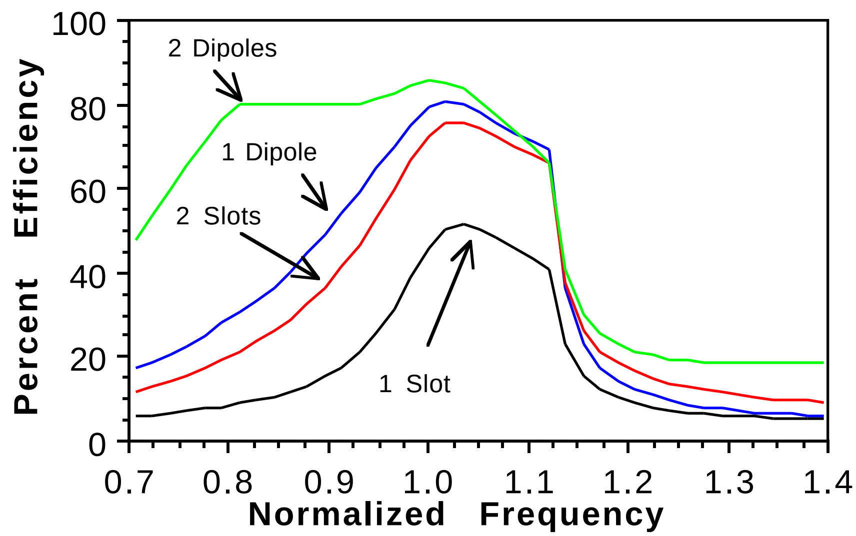


Figure 4.10 Efficiency vs normalized frequency for single and broadside spaced twin elements on a $\varepsilon_1 = 4$, $\varepsilon_2 = 4$, $\varepsilon_3 = 13$ layered dielectric structure. The separation for the twin slots is $0.293\lambda_o$ and the separation for twin dipoles is $0.244\lambda_o$.at $f_N = 1$.

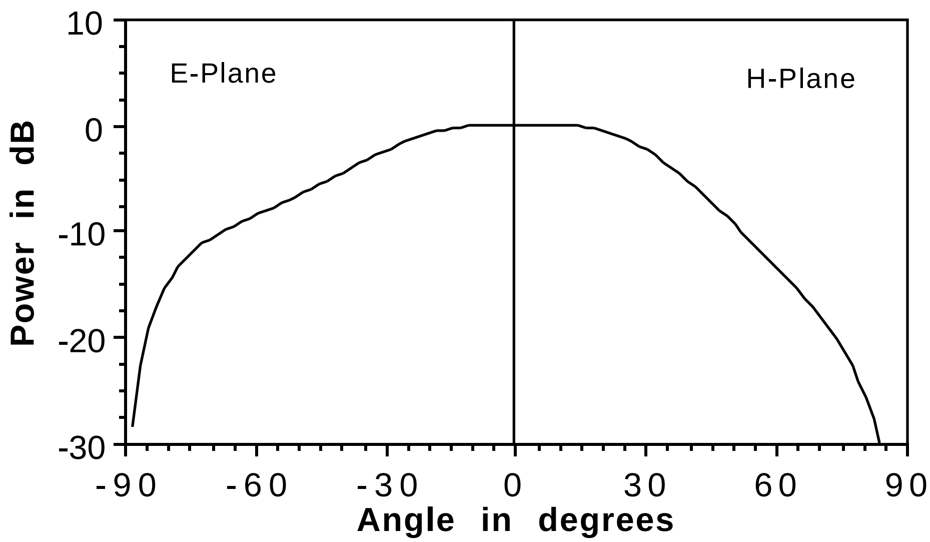


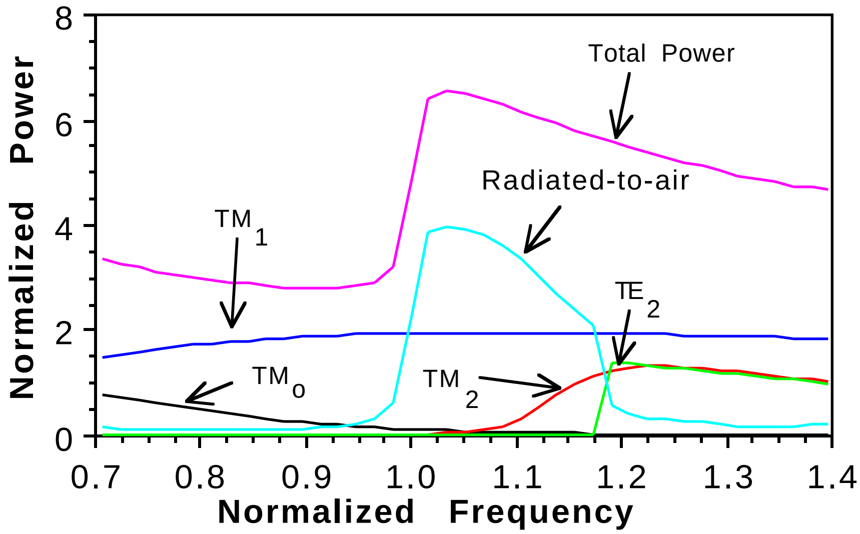
Figure 4.11 Beam pattern for either a single slot or a single dipole on a $\varepsilon_1 = 4$, $\varepsilon_2 = 4$, $\varepsilon_3 = 13$ layered dielectric structure. The gain for a single slot is 6.2dB, and for twin slots is 8.9dB. The gain for a single dipole is 8.75dB and for twin dipoles is 9.5dB.

previous cases, due to the lower contrast in dielectric constant between the second and third layers.

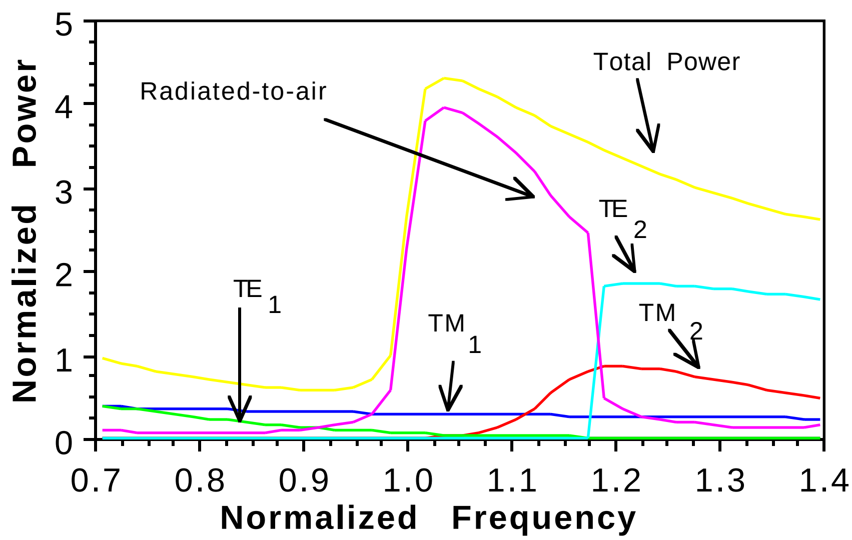
4.3 Five Layer Case:

Five layer structures are very similar to three layer structures, so we will show only two cases. The main difference is that as more layers are added in the resonant configuration, the beamwidth narrows. The two structures considered here are of two different types. The first is a further extension of the "inverted" structure which is not strongly resonant, but could be used in a high f-number imaging system. The second is a strongly resonant structure which has a narrow beam. We will see that these two types of structures have different surface wave modes that carry most of the power, and that losses become more important as the gain or "resonance" of the structures is increased.

The first structure considered has the "inverted" dielectric configuration of $\varepsilon_1 = 4$, $\varepsilon_2 = 2.4$, $\varepsilon_3 = 13$, $\varepsilon_4 = 4$, and $\varepsilon_5 = 13$. Figure 4.12 shows the power distribution curves for the single element cases. We see that the dominant mode that carries guided wave power for the slot antenna is the TM_1 mode; the lower order TM_0 mode carries an insignificant amount of power by comparison. Again, since only one guided mode carries power, twin slots should yield a significant improvement in efficiency over a single element. In contrast to the slot, a single dipole delivers almost no power to guided waves compared to the amount of power radiated to air; this is because the dipole is located between the two low dielectric constant layers, as discussed in the 4-2.4-13 three layer case. The efficiency calculations for this structure are shown in Figure 4.13. As



a) Slot



b) Dipole

Figure 4.12 Normalized power vs normalized frequency for a) a single slot, and b) a single dipole on a $\varepsilon_1 = 4$, $\varepsilon_2 = 2.4$, $\varepsilon_3 = 13$, $\varepsilon_4 = 4$, $\varepsilon_5 = 13$ layered dielectric structure. Note that the TM_1 mode carries the majority of power in both the slot and dipole cases.

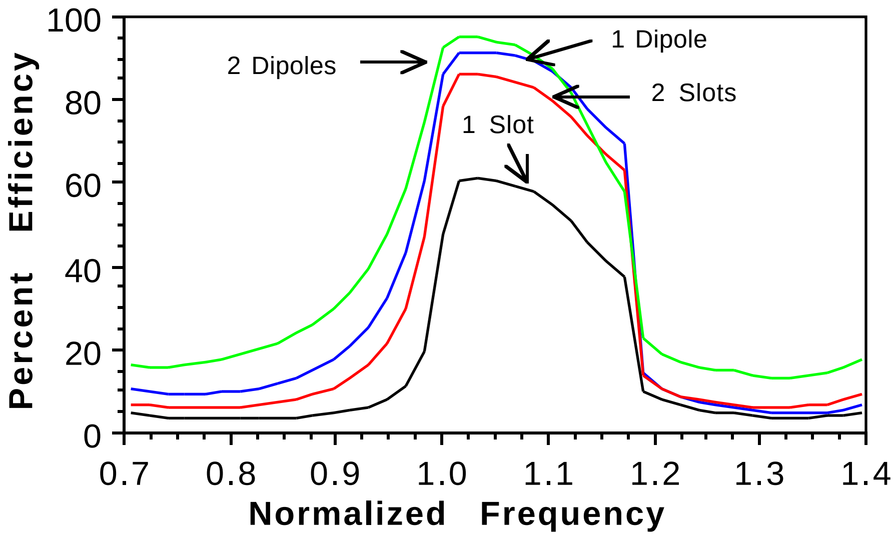


Figure 4.13 Efficiency vs normalized frequency for single and broadside spaced twin elements on a $\varepsilon_1 = 4$, $\varepsilon_2 = 2.4$, $\varepsilon_3 = 13$, $\varepsilon_4 = 4$, $\varepsilon_5 = 13$ layered dielectric structure. The separation for the twin slots is $0.317\lambda_o$ and the separation for twin dipoles is $0.366\lambda_o$.at $f_N = 1$.

expected from Figure 4.12, the results show that the dipole is a very efficient radiator (86% at $f_N = 1$ for a single dipole, 92% for broadside spaced twin dipoles) on this five layer stack, and that while a single slot is not particularly efficient (47% at $f_N = 1$), broadside-spaced twin slots are quite efficient (78%).

The beam pattern for the 4-2.4-13-4-13 stack is shown in Figure 4.14. The beam patterns for the slot and dipole are very similar, as in the three layer cases, so we show only the beam pattern for the slot. The E- and H-planes are quite symmetric, somewhat more so than for the 4-2.4-13 three layer stack, due to the increase in the number of layers. The 3 dB beamwidth of this pattern is about 18 degrees, narrower than the 4-2.4-13 three layer patterns discussed earlier. For a single slot, this structure yields a high boresight front-to-back ratio, about 70 in power, but since the beam pattern is narrow, the total integrated power radiated through the dielectric is only about 2.6 times the total integrated power radiated directly to air (the backside).

An even narrower beam pattern can be obtained if the contrast between the adjacent layers is increased. We will consider the "symmetric" structure where $\varepsilon_1 = 13$, $\varepsilon_2 = 1$, $\varepsilon_3 = 13$, $\varepsilon_4 = 1$, and $\varepsilon_5 = 13$, which corresponds to a stack of substrates with quarter-wavelength air gaps in between. The power distribution is very similar to the 13-1-13 three layer case previously considered. The situation is now quite different, however, from the previous five layer case: it is now the TM_0 mode which is dominant, while the higher order modes carry an insignificant amount of power . A single slot will not be very efficient on this type of structure, but since there is only a single TM mode carrying most of the guided wave power broadside twin slots should provide significant

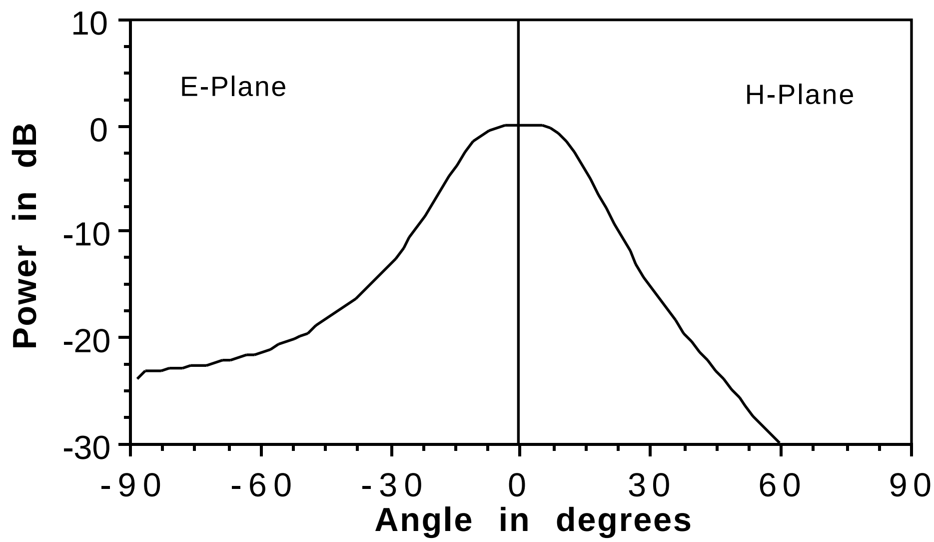


Figure 4.14 Beam pattern for either a single slot or a single dipole on a $\varepsilon_1 = 4$, $\varepsilon_2 = 2.4$, $\varepsilon_3 = 13$, $\varepsilon_4 = 4$, $\varepsilon_5 = 13$ layered dielectric structure. The dielectrics and the ground plane are assumed lossless. The gain for a single slot is 13.0dB, and for twin slots is 15.8dB. The gain for a single dipole is 16.0dB and for twin dipoles is 16.5dB.

improvement, as shown by Figure 4.15. The twin slots are now actually more efficient than twin dipoles, as in the previous three layer cases when an $\varepsilon_1 = 13$ substrate was used. The efficiency appears to be constant over a large range of frequencies, but as in the three layer case, this is because the beam pattern splits into a "cone" which spreads as frequency increases. The efficiencies are about the same for this five layer case as for the 13-1-13 three layer case. This suggests that adding more layers will not necessarily increase the efficiency of multi-layer structures.

The term "strongly resonant" is used because, as the contrast in dielectric constant between adjacent layers in these resonant stacks increases, the TE and TM surface impedances looking into the stack from the ground plane (given by equation 2.4) vary more rapidly as a function of k_ρ. On boresight (i.e. $k_\rho = 0$), the impedance is also dramatically decreased when such a stack is used (as can be seen from equation 4.1 by including the factors ε_4 in the numerator and ε_5 in the denominator). For instance, the 13-1-13-1-13 stack produces a boresight surface impedance of less than 0.2 Ω. Since the power density radiated-to-air is inversely related to the surface impedance, the maximum in the beam pattern coincides with this minimum in impedance; i.e. the beam pattern maximum occurs at $k_\rho = 0$. As k_ρ increases, the surface impedance (TE or TM) looking into the stack rapidly increases from its minimum value on boresight, causing a rapid decrease in antenna pattern gain with increasing angle. Thus, the resulting beam pattern will be correspondingly narrow. In this sense, we refer to the stack as "strongly resonant."

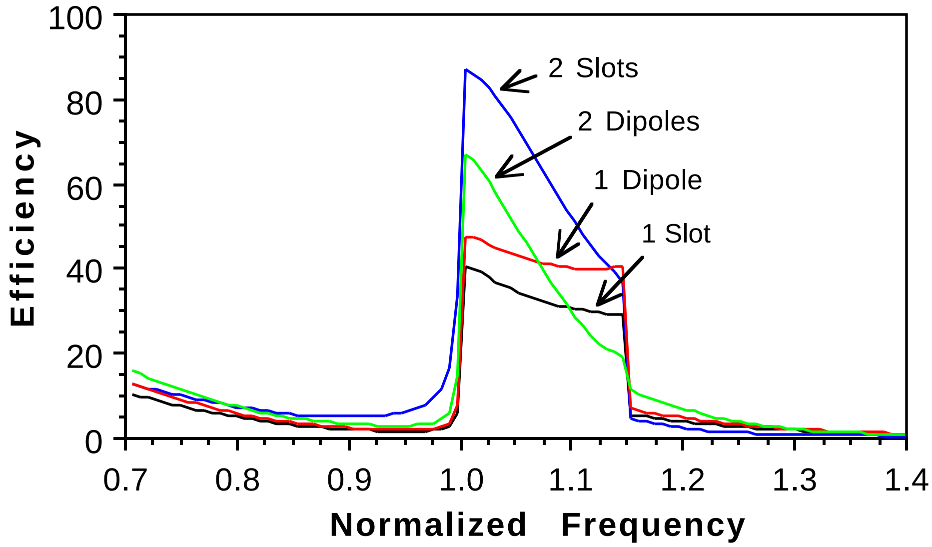
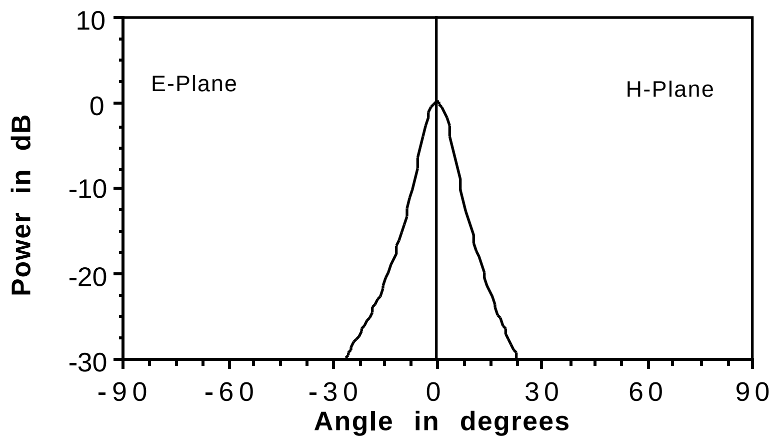


Figure 4.15 Efficiency vs normalized frequency for single and broadside spaced twin elements on a $\varepsilon_1 = 13$, $\varepsilon_2 = 1$, $\varepsilon_3 = 13$, $\varepsilon_4 = 1$, $\varepsilon_5 = 13$ layered dielectric structure. The separation for the twin slots is $0.341\lambda_o$ and the separation for twin dipoles is $0.488\lambda_o$. For this calculation, the dielectrics and the ground plane are assumed to be lossless.

Figure 4.16 shows the beam patterns for this stack. Due to the strongly resonant nature of the 13-1-13-1-13 structure the beamwidth for lossless dielectrics and ground plane is now very narrow, about 4º (Figure 4.16a). In such strongly resonant structures, however, the losses in the dielectric and the ground plane are much more important than in the previously considered cases. Figure 4.16b compares the E- and H-plane patterns for the 13-1-13-1-13 stack assuming both ground plane and dielectric losses are zero, assuming the loss-tangent in the $\varepsilon_r = 13$ (GaAs) layers is $5x10^{-4}$ [43] with a lossless ground plane, assuming lossless dielectrics with a copper ground plane of surface impedance about .1 Ω (i.e. $\sigma = 5.8x10^7$ mhos / meter, 1 μm thick, at a frequency of 94 GHz), and assuming both types of losses. When both types of losses are included, the boresight power is reduced by about a factor of 2.5, and the total integrated power is reduced by about 25%. It is clear that ground plane losses are as important as dielectric losses, if not more so near boresight. This is where the surface impedance looking from the ground plane into the dielectric stack is the lowest, and in fact is comparable to the ground plane impedance for this strongly resonant stack. Thus, although in principle it is possible to synthesize a very narrow beam pattern using properly chosen multilayer substrates, finite conductivity and dielectric losses will probably restrict their practical application significantly.

4.4 Beam Pattern Measurements

To test the validity of the calculated beam patterns for these layered structures measurements were made at 10GHz. To construct a layered substrate Emerson and Cumming Stycast Hi-K dielectric and polyethylene sheets were used. The dielectrics



a) Lossless case

b) Comparison of Losses

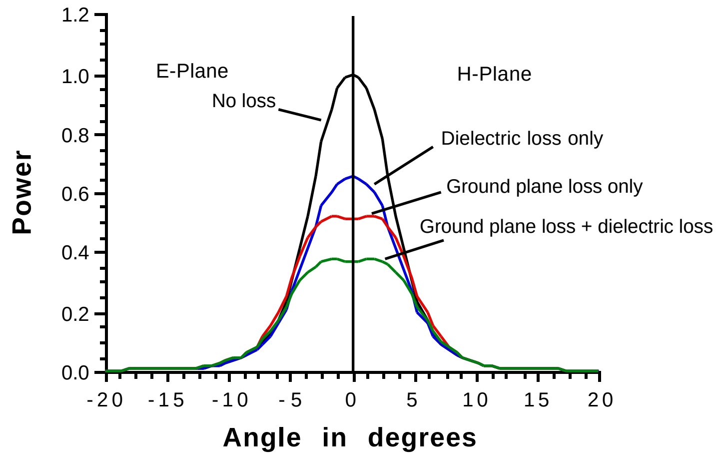


Figure 4.16 Beam pattern for either a single slot or a dipole antenna on a $\varepsilon_1 = 13$, $\varepsilon_2 = 1$, $\varepsilon_3 = 13$, $\varepsilon_4 = 1$, $\varepsilon_5 = 13$ layered structure. (a) The dielectric structure is assumed to be lossless. The gain for a single slot is 21dB, and for twin slots is 26dB. The gain for a single dipole is 22dB and for twin dipoles is 24dB. (b) Comparision of the lossless case to the cases with various losses included. The dielectric loss is assumed to be confined to only the odd layers ($\varepsilon = 13$ layers) and a loss tangent of 0.0005 is used. The ground plane is assumed to be 1μm thick with a conductivity of $5.8\text{x}10^7$mhos/meter (i.e. copper).

were all machined to be nominally a quarter of a dielectric wavelength thick at 10GHz. The ground plane was made by placing strips of 3M copper foil tape on the back surface of the first layer of the substrate. Additional layers were then added as desired. The detectors used were zero-bias Schottky diodes made by MACOM. The detectors were soldered across the slot antenna. For the slot built on a $\varepsilon_r = 4$ substrate, the slot was 1cm long and .3 cm wide, the slot on an $\varepsilon_r = 13$ substrate was .5cm long and .2 cm wide. A motorized azimuth-elevation antenna positioner was used to hold and move the antenna. The ground plane was fairly small, being only 3.3 free space wavelengths on a side; consequently, there were some problems with finite ground-plane effects for E-plane measurements. Most of the H-plane patterns, however, did not show such effects. All beam patterns (measured and calculated) are normalized to be one on boresight.

Measured and calculated H-plane beam patterns for a three dielectric layer substrate are shown in Figures 4.17 and 4.18. For Figure 4.17, the dielectrics used for layers 1 and 2 give $\varepsilon_1 = \varepsilon_2 = 4$, and for layer 3 gives $\varepsilon_3 = 13$; thus the slot is effectively on a $\lambda_d/2$ thick, $\varepsilon_r = 4$ layer, followed by a $\lambda_d/4$ thick, $\varepsilon_r = 13$ layer. The losses in the dielectric and ground plane have been included to calculate the beam pattens, although these effects are quite small. The finite length of the slot was accounted for in all of the patterns presented in this section by assuming a sinusoidal field distribution in the slot. This effect, however, was also quite small. The effect of the finite width of the slot in all of the calculated beam patterns presented in this section was neglected. The agreement between theory and experiment clearly shows that the patterns are dominated by the dielectric. The calculated efficiency of a single slot on this structure assuming lossless dielectrics would be about 45%. If twin slots

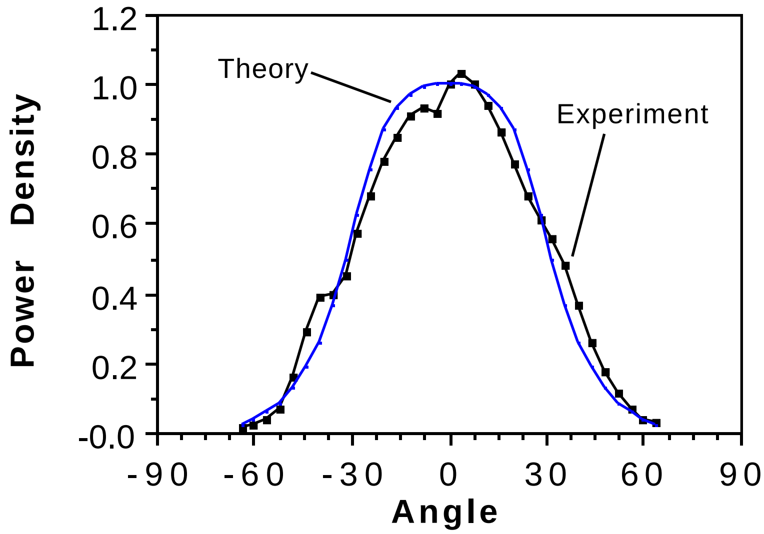


Figure 4.17 H-plane pattern for a slot with $\varepsilon_1=\varepsilon_2=4$, and $\varepsilon_3=13$. Measurements made at 10GHz. Dielectrics are slabs of Emerson and Cumming Stycast Hi-K dielectrics.

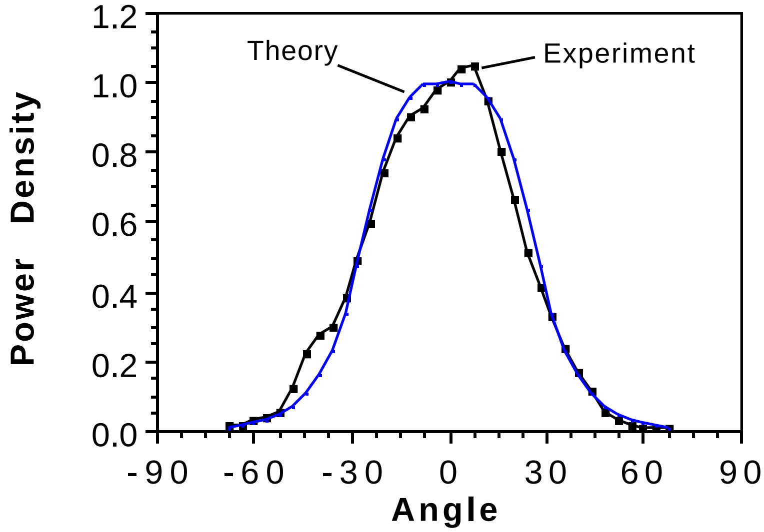


Figure 4.18 H-plane pattern for a slot with ε_1=13, ε_2=2.4, and ε_3=13. Measurements made at 10GHz.

are employed in a manner similar to that described in Chapter 3 the efficiency can be increased to about 72%. The calculated efficiency of a single dipole placed between layers 1 and 2 would be 79%, while broadside twin dipoles would give 85%. Measurements and calculations with twin slot antennas show no appreciable difference in the beam pattern compared to a single element slot.

Figure 4.18 shows the measured and calculated pattern for a three layer structure with ε_1 =13, ε_2 = 2.4 and, ε_3 = 13. Again we see that the agreement is fairly good. Because this three layer stack is more resonant than the three layer structure discussed above, the beam pattern is slightly narrower. Here the measured front-to-back ratio for the single slot is 36, with a predicted value of 70. This discrepancy is probably due to the fairly large detector diode on the backside of the substrate.

Figure 4.19 shows the measured and calculated H-plane patterns for a five layer structure with ε_1 = 4, ε_2 = 2.4, ε_3 = 13, ε_4 = 4, and ε_5 = 13. Here the beam pattern is much narrower than for the three layer cases. We also have measured a front-to-back ratio that is close to the value predicted by theory: 66 measured, 70 calculated. The E-plane pattern (not shown) is identical to the H-plane pattern and agrees with experiment equally well. In this case the lobes due to finite ground plane effects are conspicuously absent from the measured E-plane pattern because of the dielectric layers. Again assuming lossless dielectrics, the efficiency of a single slot antenna on this structure is calculated to be about 47%, while the twin elements would give about 79%. The single dipole would have an efficiency of 86%, and broadside twin dipoles 92%. The dipoles are more efficient than the slots because the initially low dielectric constant layer followed by the subsequent higher

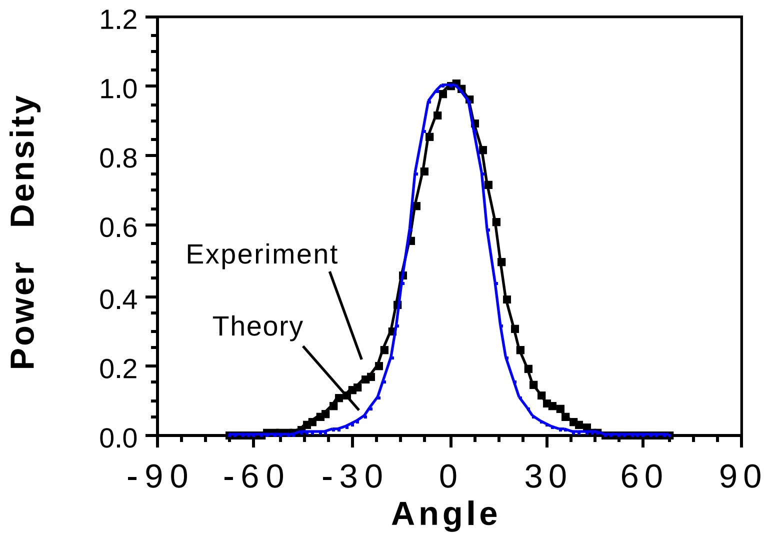


Figure 4.19 H-plane pattern for a slot with ε_1=4, ε_2=2.4, ε_3=13, ε_4=4, and ε_5=13. Measurements were made at 10GHz.

dielectric constant layers tends to suppress guided mode losses to the lower order TM modes.

In order to illustrate the sensitivity of antenna patterns on these layered structures we have also considered the effects of a small air-gap between the dielectric layers. Figure 4.20 shows the H-plane pattern of the same structure as that used in Figure 4.18 with a 40mil ($0.03\lambda_o$) air gap between the first and second layers. The rather dramatic result is the appearance of "horns" at 28^o from boresight. The fit between experiment and theory was improved if the assumed values of ε_1 and ε_3 were changed from 13 to 12.8 (the material is only guaranteed to be within 10% of the nominal value of 13). This small change in dielectric constant reduced the magnitude of the "horns" by a factor of 0.7. Both calculations and measurements show that the location and size of these peaks are more sensitive to parameter errors than when the beam is concentrated along boresight (i.e no air-gap). For this dielectric structure our calculations show the same results in the case of the dipole when the same air-gap is placed at the interface between layer 1 and layer 2 (i.e. the interface containing the dipole). It is worth noting that this gap, scaled to 94GHz, would be approximately the thickness of a human hair.

4.5 Conclusion

We have discussed the effects of layered substrates on the efficiency and beam patterns of slot and dipole antennas, and, in particular, we have shown that resonant dielectric stacks can increase the radiation-to-air efficiency of slot and dipole antennas. Although the conditions necessary to maximize power radiated to air for dipoles and slots appear to be the same, the efficiencies of a dipole or a slot on a

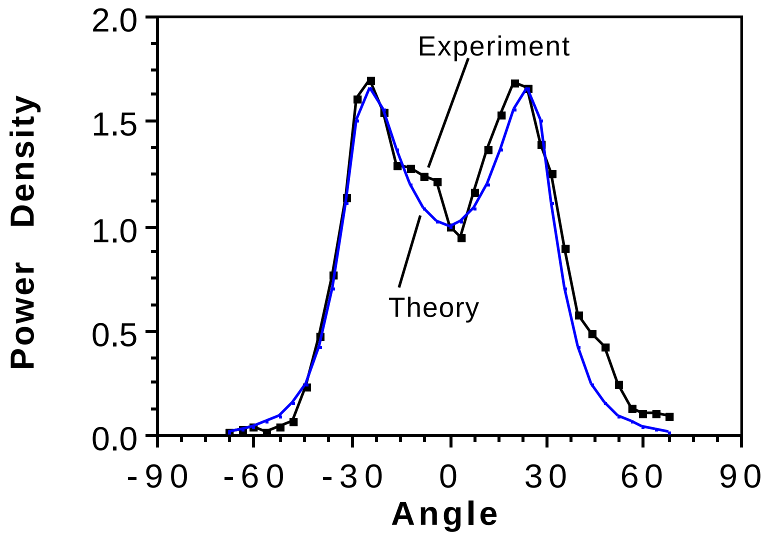


Figure 4.20 H-plane pattern for a slot with ε_1=12.8, ε_2=2.4, and ε_3=12.8 with a 40mil (0.033λ_o, where λ_o is a wavelength in free space) air gap between layers 1 and 2. Measurements were made at 10GHz.

given dielectric stack may be quite different. This is due to the differences in coupling between guided waves and the radiating element.

The effect of the dielectric stacks on the guided waves can be summarized as follows. Increasing the contrast between alternating layers tends to reduce the power coupled to the higher order guided modes. If the substrate and the subsequent odd-numbered layers have the same dielectric constant, most the the power delivered to guided waves by either the slot or the dipole will be in the TM_o mode. However, if a substrate with a lower dielectric constant than those of the subsequent odd-numbered layers is used (an "inverted" structure), the lower order TM and TE guided modes will not be strongly excited. This increases the efficiency of single element radiators substantially, especially in the case of the dipole.

The effect of the layered stacks on the beam patterns can be summarized very simply. Resonant structures that have three or more layers will have beam patterns which will be largely determined by the dielectric layers. The topmost two layers (i.e. layers 2 and 3 for a three-layer structure) are the most important in determining the beamwidth. Changing the dielectric constant of the substrate affects the beam pattern only slightly. Increasing the number of layers and increasing the contrast between the layers narrows the beam patterns, although ground plane and dielectric losses become more important in these cases.

The fabrication of these structures should be fairly straightforward because none the parameters of construction will be in the extreme. The thicknesses will range from 4 or 5 mils to 16 mils depending on the frequency of operation and the dielelctric constant. The experiments showed that it is important to have all of the dielectric layers pressed together tightly with no air gaps in between them. We also found that the substrates must flat so that the beam pattern will not be adversely affected.

Although dipoles have the highest calculated efficiencies on these structures, the problems associated with feed networks for these antennas cause practical limitations on their usefulness in array applications. Slot antennas, however, have the advantage that the feed network can easily be isolated from the side of the antenna that receives the incident radiation (by the slot ground plane). Even though a single slot is not a very efficient radiator-to-air on these structures (less than 50% in most cases), the use of broadside-spaced twin slots dramatically improves this efficiency making the slot antenna a viable option. In conclusion, for imaging arrays employing either slots or dipoles, multilayered structures are an attractive alternative because of the control that can be exerted over the beam patterns of the elements by the choice of the dielectric layers and because of the relative simplicity of fabrication of these structures. Thus, layered substrates should provide another means to fabricate efficient printed circuit antennas that can operate at millimeter-wave and far-infrared frequencies.